Compensated Mass Balance Method For Oil Pipeline Leakage Detection using SCADA

Mohamed Zaid A. Karim *mdzakarim6@yahoo.com*
Faculty of Engineering/ Department of Electrical Engineering
University of Aden
Aden/ Yemen

Amr A. Aziz Gaafar Alrasheedy *amr_alrasheedy@yahoo.com*
Faculty of Engineering/ Department of Electrical Engineering
University of Aden
Aden/ Yemen

Abstract

Having extracting oil from reservoir below the ground surface, and after processing, the products are transported through a network of oil pipelines to oil terminals. Thus, oil pipelines play a major role of the economic structure. However, oil pipelines could be subjected to damage due to many reasons like (i) Pipeline corrosion or wear, (ii) Operation outside the design limits, (iii) Unintentional third-party damage and (iv) Intentional damage. As a result of this damage, oil would leak from pipelines, which leads to loss of life and property, cost of lost product and line downtime, environmental cleanup cost, possible fines and legal suits.

The biggest challenge in this industry is to come up with a pipeline leak detection method that will accurately detect leaks in a timely fashion.

There are several methods which lead to detection of pipeline leakage. In most Yemeni oil fields pipeline leakage is detected by fiber optics sensing method which is expensive or by visual inspection using experienced personnel who walk along a pipeline, looking for unusual patterns near the pipeline.

In this paper, we are going to implement a different and cost effective method using Supervisory Control and Data Acquisition (SCADA) system.

Simulation has been performed using Rockwell Automation Software Products. The results so obtained are presented and discussed.

Keywords: SCADA, Leak Detection, Oil Pipeline, Mass Balance, Pump Failure.

1. INTRODUCTION

According to Yemeni Ministry of Oil & Minerals, the current average daily oil production in Yemen reached about 274,266 Barrel of Oil per Day (BOPD), from 13 producing blocks. All these products are transported through a network of oil pipelines into oil terminals [1]. These pipelines could be subjected to damage. So it is necessary to cease oil leakage by detecting it and acting to stop it as fast as possible [1].

Methods used to detect pipeline leakage are divided into two categories. External based methods which detect leaking product outside the pipeline and include traditional procedures such as right-of-way inspection by line patrols that walk along the pipeline, looking for unusual patterns near the pipeline, as well as technologies like hydrocarbon sensing via fiber optic or dielectric cables [2, 3]. However, these are quite expensive.

As an alternative, internal leak detection method that uses software algorithms and instrumentations to measure and monitor the internal pipeline parameters (i.e. pressure, flow, temperature, etc.) [2], is less expensive as compared to the external one [2, 4]. These parameters are fed to (SCADA) systems, which are computer-based systems [2]. SCADA system uses a software algorithm to calculate the inventory of the line at all times and compare this with the accurate measurements at any section in the system. The effects of pressure and temperature on line dimensions, for example, can be calculated to provide an accurate estimate of the mass of fluid in the line [4], and hence recognize hydraulic anomalies [5].

SCADA system gathers, processes, displays and controls data from field instrumentation [5]. For these reasons, most pipeline systems today employ some form of SCADA using commercially available or custom-designed software packages to monitor and recognize hydraulic anomalies and detect leakage in pipelines [2].

In block S1 in Shabwa governorate (Yemen) with daily production about 10,000 BOPD, an internal method called Pressure Point Analysis (PPA) is used for leakage detection. This paper proposes another internal method called Compensated Mass Balance method using SCADA. This method is discussed, simulated and analyzed. Comparison between the two methods is also performed.

2. PRESSURE MONITORING

When a leak suddenly occurs in a pipeline, there is a sudden change in the pipeline pressure [6]. These changes or disturbances can be useful in detecting the leakage; Pressure Monitoring method can detect the leak as following:

2.1. Pressure Point Analysis (PPA)

PPA leak detection method is based on the premise that the statistical analysis property of a series of pressure measurements taken on a pipeline is different before and after leak occurrence [7].

Pipeline pressure falls too rapidly in case of leak [8]. This leak can be detected by comparing pressure of pipeline at a single point and comparing it against the statistical pressure measurements [7]. Dedicated software will determine if the behavior of these two signals contains an evidence of leak [9], when the pressure falls below a lower limit [10].

2.2. Rarefaction Wave

When a leak occurs, there is a sudden drop in pressure at the leak followed by rapid line an increase in the pressure (re-pressurization) for a few milliseconds later. The resulting low-pressure expansion wave travels at the speed of sound through the liquid away from the leak in both directions [4]; following this wave there is a general loss of pressure in the pipeline [7].

Due to these disturbances (the sudden pressure drop, the rapid pressure increase and after that the general loss of pressure), so the pressure in pipelines can be recognized by the upstream and downstream pressure transmitters, and hence the pressures values will be below the lower limit after that will be above the higher limit which will trigger the leak alarm.

However the main drawback in pressure monitoring method is that it requires that all events other than leaks that may cause a pressure to decline and rise, such as operational changes to the pipeline (i.e. start/stop shipping pump, opening and closing valves, and flow rate increase), must be identified so that the leak detection can be inhibited until the pipeline returns to steady state operation to avoid the false alarms [8].

3. BALANCING METHODS

The mass balance method is based on the equation of conservation of mass. In the steady state, the mass entering a leak-free pipeline will balance the mass leaving it. In general, the difference in mass at the two ends must be balanced against the change of mass inventory of the pipeline [5]. Over any given period of time we can say:

$$M_{pipe} = M_1 - M_2 \qquad (1)$$

Where:

M_1 is the inlet (upstream) mass flow rate (kg/s)
M_2 is the outlet **(downstream)** mass flow rate (kg/s)
M_{pipe} is the change of mass **inventory of the pipeline per unit time** (kg/s)

$M_1$and M_2 are obtained by software as (FT_1 x ρ_1) and (FT_2 x ρ_2) respectively, where FT_1 and FT_2 are respectively the upstream and down downstream flow rates measurements taken from the instruments and

ρ_1 and ρ_2 are the fluid densities at the upstream and downstream of the pipeline respectively

In principle, the mass in the pipe depends on the density of the product multiplied by the volume of the pipeline. Both are functions of temperature and pressure. The density is also a function of the composition of the product. Any addition in the mass imbalance indicates a leak. This can be quantified by rearranging Equation (1) and adding a term for leak mass flow M_{leak} gives:

$$M_{leak} = M_1 - M_2 - M_{pipe} \qquad (2)$$

Where M_{leak} is the leak mass flow

Mass balance methods use the principle of mass conservation; i.e. mass is conserved if there is no leak, in general, the inventory of the pipeline for length (L) changes over time because of changes in the fluid density ρ and cross sectional area A.

By dividing the pipeline into segments (n), the temperature, pressure, and density are assumed to be uniform results in the line fill calculation as well as the uniform segment density ρ_n. The line pack equation will be as follows [11]:

$$M_{pipe} = \int_0^L \rho(x)A(x)dx \qquad (3)$$

Where A is pipeline cross-sectional area (m^2)

3.1. Uncompensated Mass Balance

It is also known as Line Balance, in this method there is no compensation for the change in pipeline inventory due to pressure and temperature [7], so the fluid density (ρ) and pipeline cross-sectional area (A) are assumed to be constant [9], therefore M_{pipe} becomes negligible [5], so the leak mass flow equals the difference between the inlet mass flow rate and the outlet mass flow rate**.** Equation (2) becomes:

$$M_{leak} = M_1 - M_2 \qquad (4)$$

As a result of the above assumption, the method doesn't take into account the changes in fluid density due to pressure variations, and changes in actual dimensions of pipeline due to temperature changes. Hence, it becomes a susceptible to false alarms [2].

3.2. Compensated Mass Balance

Compensated mass balance uses a bulk modulus of elasticity ε (which is a material property characterizing the compressibility of a fluid and how easy a unit of the fluid volume can be changed when changing the pressure applied on it) [2], along with an average temperature and pressure over the entire length of the pipe [11]. The inventory of the pipeline is usually calculated by dividing the pipeline into segments and assuming steady state pressure and temperature profiles from one end of the pipeline segment to the other, and calculating an average density for the segment [8].

3.3. Model of Compensated Mass Balance

Model of the compensated mass balance uses the real time transient models (RTTM) method. The RTTM uses the computational power of modern computers with the help of software algorithms for evaluation of leaks and make it possible to compute density along the pipeline [6]. Software-based method that calculates the flow balance (FB) as the difference between the M_1 and the M_2 as given below in Equation (5).

$$FB = M_1 - M_2 \quad \text{(kg/s)} \tag{5}$$

In addition, a hydraulic transient computer model is used to calculate the mass inventory of the pipeline which is referred as packing rate (PK) in Kg/s. The packing rate is calculated by the transient model from pressure and temperature or density data provided by SCADA system instrumentations. A quantity called mass balance (MB) is calculated as the flow balance minus the packing rate [9], as given in Equation (6).

$$MB = FB - PK \quad \text{(kg/s)} \tag{6}$$

Ideally, the mass balance will always be calculated as zero. A positive imbalance is interpreted as a leak [9]. The advantage of this system over PPA or uncompensated mass balance is that system transients like pump start up and shutdown will not generate alarms [9, 10].

3.2.1. Modeling Equation

The transient pipeline flow model, which is used to calculate packing rate, is the heart of a pipeline modeling system. The model computes the state of the pipeline at each time interval for which data are available. The state of the pipeline is defined as a set of pressures, temperatures, flows, and densities that describe the fluids being transported at all points within the system. These quantities are the solutions of a set of equations that describe the behavior of the pipeline system. These basic equations are the continuity equation which enforces conservation of mass, the momentum equation which describes the force balance on the fluid within a section of pipeline, and the energy equation which states that the difference in the energy flow into and out of a section equals the rate of change of energy within the section. Now the question is how to solve the above three equations. The answer is by finding a relation between the pressure, density, and temperature of the fluid [4].

Using an equation of state which relates the density of the fluid to its pressure and temperature, the density can be calculated from an average temperature and pressure over the entire length of the pipe [6].

The packing rate is calculated by assuming steady state pressure and temperature profiles from one end of the pipeline to the other, and calculating an average density of the fluid along the pipeline [8], as

$$\rho_{av} = \rho_o\left[1 + \frac{(P_2 - P_1)}{\varepsilon} + \alpha(T_2 - T_1)\right] \quad (7)$$

The density is then multiplied by the pipeline volume to find the **fluid mass inside the** pipeline

$$\text{Fluid mass} = \text{Pipeline Volume} \times \rho_{av} \quad (8)$$

Finally the **fluid mas**s is divided by the time (in seconds) to obtain the packing rate

$$PK = \text{Fluid mass}/t \quad (9)$$

Where:

ρ_{av} is the average density	(Kg/m^3)
ρ_0 is the reference or real density	(Kg/m^3)
P_1 , P_2 is the upstream and downstream pressures calculated by software	(GPa)
ε is the bulk modulus fluid elasticity	(GPa)
T_1 , T_2 is the upstream and downstream temperatures calculated by software	(°C)
α is the temperature expansion coefficient	(1/°C)

3.2.2. Program Algorithm

Real-time transient modeling (RTTM) is a technique that uses the full data-gathering capabilities of modern digital systems and the computational power of small computers to give accurate ‘‘snapshots’’ of the pipeline. The whole system is under the control of a SCADA package of programs, which gather data from field instrumentation, process the data, control the running of the transient pipeline model, and activate the alarm and leak location routines. The SCADA interface is responsible for acquiring the data from the SCADA system and relating them to the model representation of the line. The model provides data on the flow conditions within the line at intervals ranging from seconds to minutes, depending on operational needs. The real-time applications modules will run based on the availability of data from the measurement system and the pipeline model. These are the leak detection and location routines in the context of integrity monitoring [4].

When a leak occurs, the difference (FB - PK) become larger, but less than a set point (which is 10% of total flow), the model system does not account for a leakage. If this difference exceeds preselected set points, a leak alarm is declared.

Once the leak detection module declares a leak, the location routine is activated. The location is calculated using the upstream and downstream mass flow rates, as per Equation (10).

$$\text{Leak location} = \frac{M_2 \times L}{M_1 - M_2} \quad (10)$$

Where L is the pipeline length (Km)

4. SIMULATION AND RESULTS

In this section, simulation will be carried out with help of Rockwell Automation Software Products i.e. (RSLogix Emulate 5000, RSLinx, and RSLogix 5000 Enterprise Series) which provide SCADA hardware and software components, and ICONICS GENESIS32 family of web-enabled industrial automation software that offers applications for Human Machine Interface (HMI), SCADA and Control i.e. (real-time trending and data historian, summary viewing, logging and reporting) [12].

Simulation was done in two steps, first step by building a simulation for pipeline SCADA system, and second step by applying RTTM technique to detect the leak.

SCADA system, shown in figure 1, was build according to SCADA layers, which are:

- End devices or field instrumentation layer
- Programmable Logic Controller (PLC) layer
- Communication equipments layer
- Supervisory Station (SCADA Server) layer or Master Terminal Unit (MTU) which contains Object Process Control (OPC) software and HMI application. OPC software is a communication standard based on Object Linking and Embedding (OLE) technology provided by Microsoft windows that provides an industrial standard exchange mechanism between plant floor devices i.e. PLCs and client applications i.e. HMI

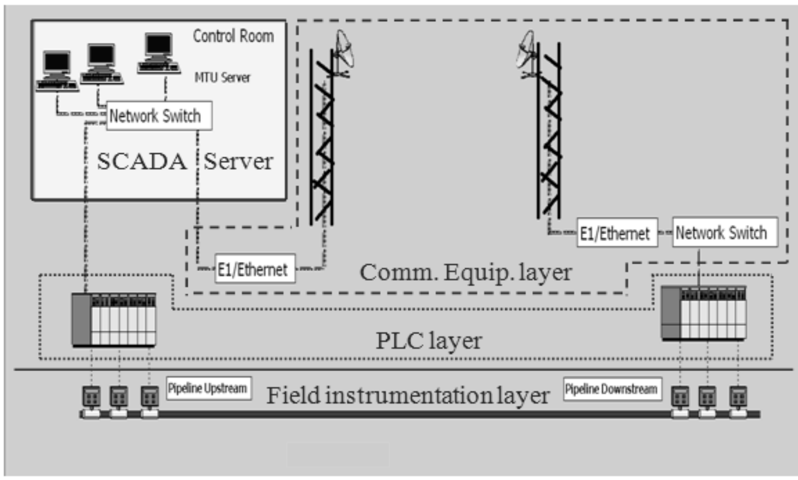

FIGURE 1: SCADA based pipeline system.

PLC layer is typically pictured as given in figure 2.

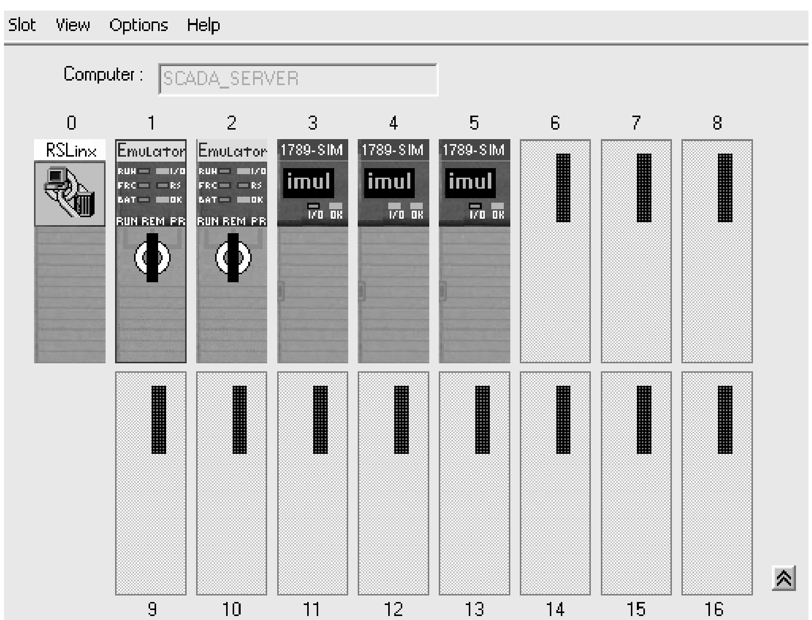

FIGURE 2: PLC layer.

The above software packages illustrate the capability of the compensated mass balanced method in recognizing the leakage of the fluid from other conditions. Some of these conditions are pump failure, flow rate increase, large leak and small leak condition.

As already mentioned, PPA method is implemented in block S1 in Shabwa governorate. With this method, all the above conditions are considered as leaks resulting, sometimes, in false alarms and unnecessary disturbances and actions.

In what follows, it will be seen that, unless the mass balance (MB) exceeds a leak set point (SP) the condition will not be considered as a leak and there will be no alarm.

The above conditions will now be simulated. However, steady state condition will first be presented to show the upstream and downstream pressures and flow rates PT_1, FT_1 and PT_2, FT_2 respectively.

PT_1 and PT_2 are the upstream and downstream pressures measurements taken from the instruments, in pound per square inch (psi) and FT_1, FT_2 are the upstream and downstream flow rates measurements taken from the instruments, in barrels of oil per hour (bbl/hr).

TT_1, TT_2 are the upstream and downstream temperature measurements taken from the instruments in (^{o}F**).**

All the above measurements are transmitted to the PLC.

The steady state values presented in Table 1 are obtained by considering the actual measurements from the field as the average values for 120 days.

Upstream Data	Downstream Data
PT_1 = 310.1975 psi	PT_2 = 246.3525 psi
FT_1 = 392.4877 bbl/hr	FT_2 = 400.3265 bbl/hr
TT_1 = 100.8502 ^{o}F	TT_2 = 92.6744 ^{o}F
ρ_1 = 0.83214 Kg/m^3	ρ_2 = 0.80966 Kg/m^3

TABLE 1: Steady State Values.

During normal operation, PT_1, FT_1 and PT_2, FT_2 are found to be steady and considered as given in the above table. The leak set point (SP) is taken as 40 bbl/hr as illustrated in figure 3. As seen, MB does not exceed SP.

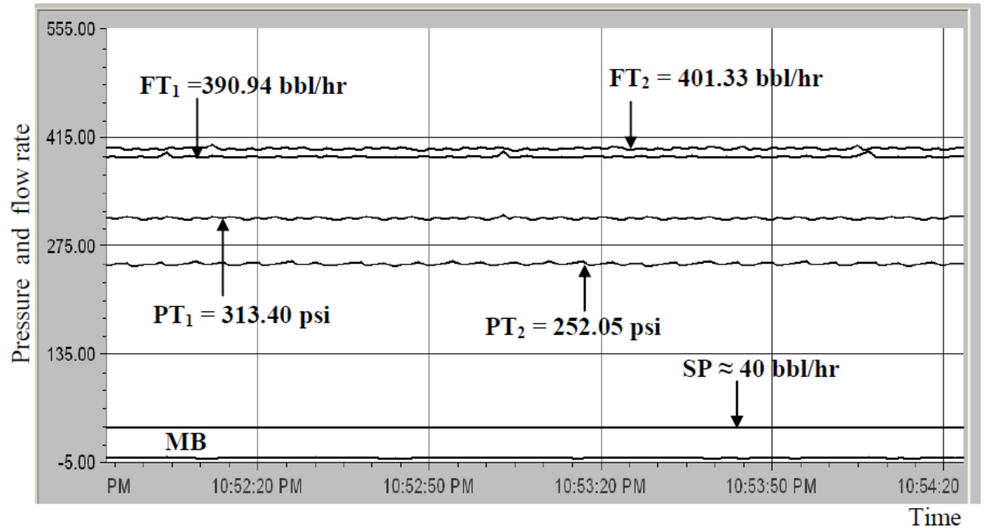

FIGURE 3: Variation of oil flow rate and pressure during steady state condition.

During normal pumping conditions a liquid will show minor transient due to pipe wall friction, reflection of pressure waves and temperature differences.

4.1. Pump Failure Condition

As long as there is no leak, the upstream and downstream flow rates drop to zero when there is a pump failure as seen in figure 4. Meanwhile, the upstream pressure falls to a value that is equal to the downstream pressure. As a result the flow rates and pressures become unsteady, for a while, in the pipeline, and hence the computed mass balance (MB) value will reduce momentarily and then comes back to its normal value. The RTTM will not trigger alarms.

In PPA method the set point is a predefined pressure value, for example 280 psi. If upstream pressure falls below this value, false leak alarm is declared.

Values of the flow rates and pressures after pump problem are indicated in the figure 4.

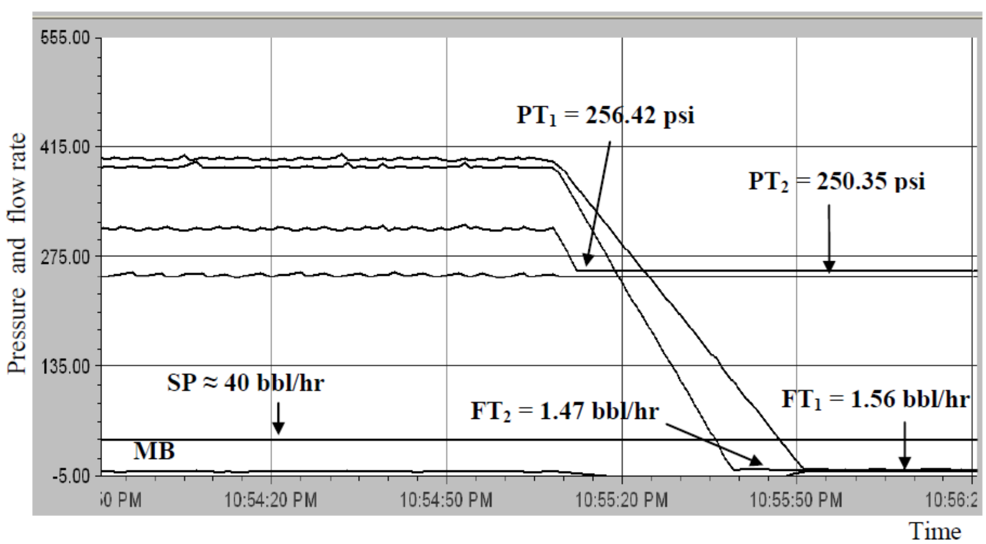

FIGURE 4: Variation of oil flow rate and pressure during pump failure condition.

4.2. Flow Rate Increase Condition

Centrifugal pumps are the most widely used in crude oil pipelines, thereby a common way to control the flow rate through the centrifugal pumps is to open/close the flow control valve which is located on the discharge side of the pump.

In this case, opening the flow control valve allows the flow rate to increase. The upstream and downstream flow rates increase to the new values and at the same time upstream and downstream pressures will increase as well. Due to these changes the mass balance (MB) value will increase for a very short time (but will not exceed the leak SP) and then comes back to its normal value and as a result there will be no leak alarm.

It is also evident that PPA method will not activate the alarm as PT_1 is more than 280 psi.

The new steady state values of the flow rates and pressures after the changes are indicated in the figure 5.

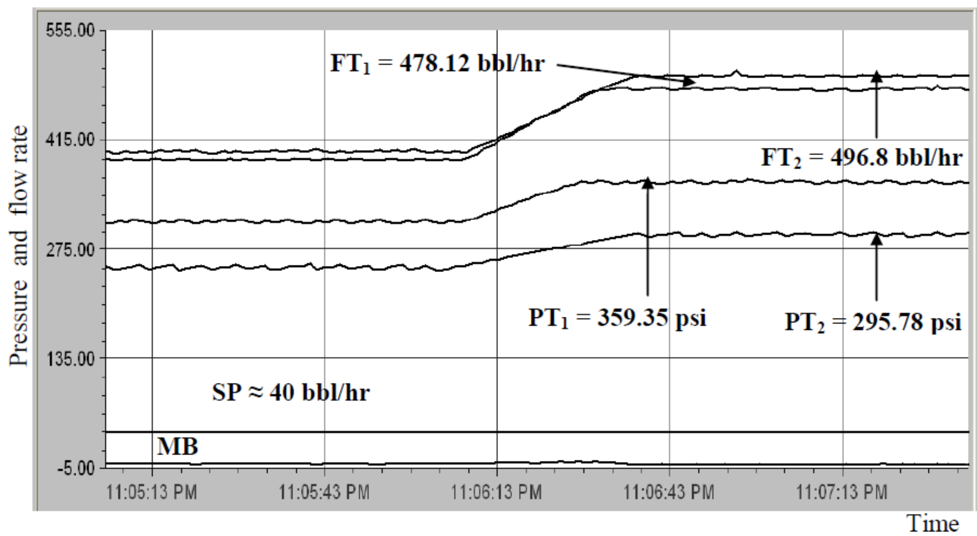

FIGURE 5: Variation of oil flow rate and pressure during flow increase condition.

4.3. Large Leak Condition

When large leakage occurs, the inlet flow rate will increase in a short time due to lower pipe flow resistance between the upstream meter and the leak, while the outlet flow will fall as mass leaves through the leak hole instead of passing through the downstream meter, see figure 6.

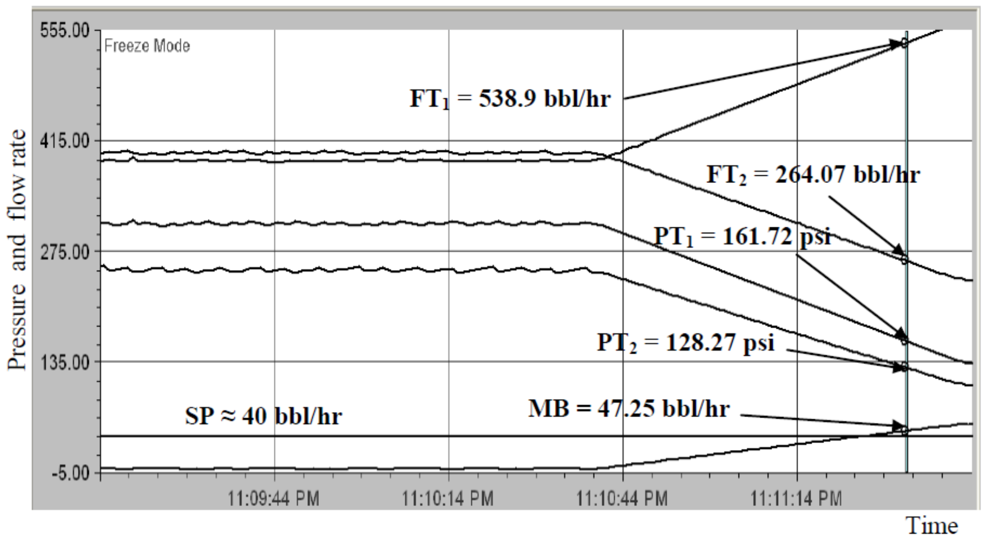

FIGURE 6: Variation of oil flow rate and pressure during large leakage condition.

The upstream and downstream pressures drop as the line is depressurized as mass leaves through the leak hole. The flow balance (FB) becomes more and more positive, at the same time the packing rate (PK) drops, and the mass balance (MB) value will increase until it exceeds the leak set point to indicate the leak rising to alarm triggering. In the figure, the indicated values are those after the leakage alarm is activated.

In PPA method the upstream pressure falls below 280 psi resulting also in a leak alarm.

Values of the flow rates and pressures after leakage occurrence are indicated in the figure 6.

It have been observed that the changes in the inlet flow rate (upstream), and the outlet flow rate (downstream) due to leakage condition in figure 6 were consistent with those changes given in figure 7 [13].

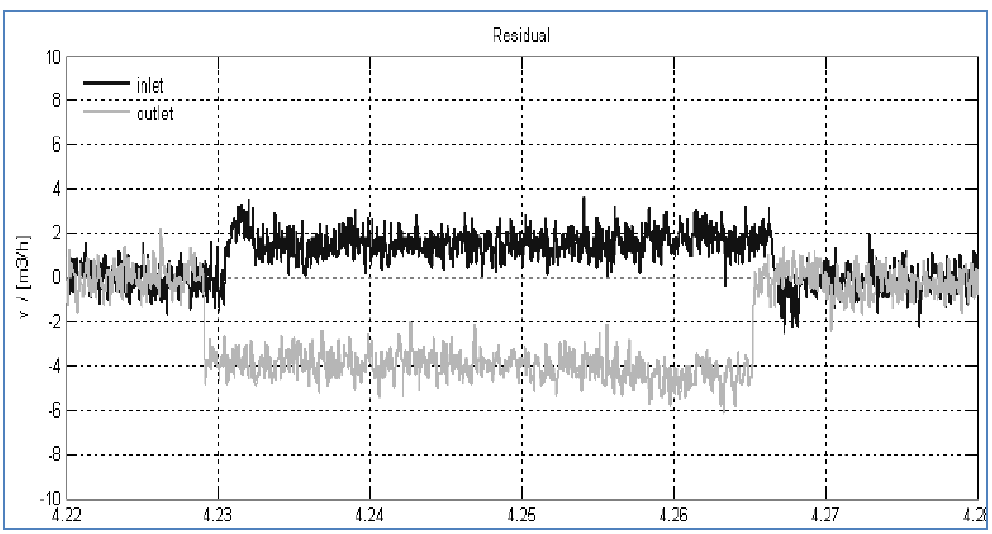

FIGURE 7: Inlet and outlet flow residual during leak trial.

4.4. Small Leak Condition

When small leakage occurs the inlet flow rate will increase slowly while the outlet flow will fall in a similar rate as shown in figure 8. The upstream and downstream pressures will also drop, which leads to an increase in the mass balance (MB) value slowly to indicate the leak. Here also, the indicated values in the figure are those after the leakage alarm is activated.

In PPA method, once the upstream pressure value drops below the set point (280 psi), the alarm will activate.

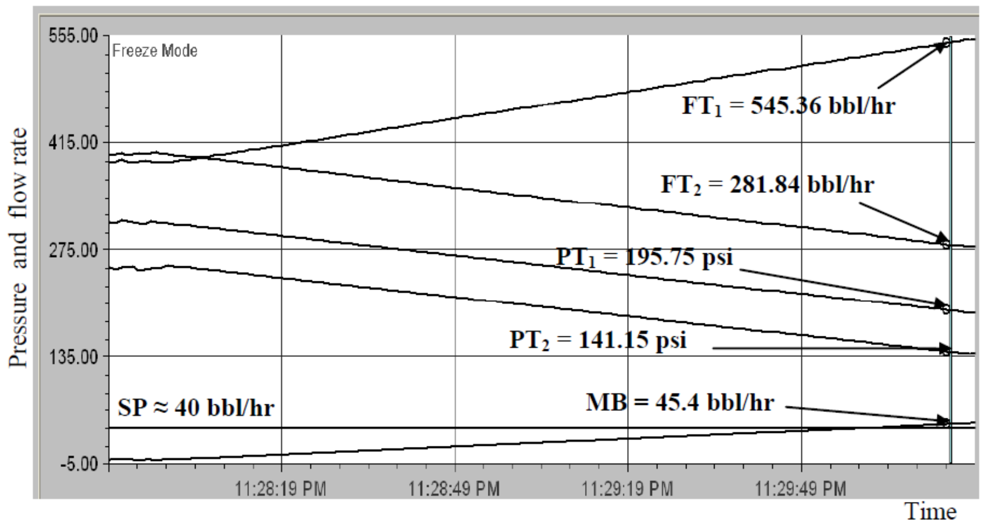

FIGURE 8: Variation of oil flow rate and pressure during small leakage condition.

As shown from the last two conditions, the time taken for the mass balance to exceed the leakage set point and declare the leakage alarm depends on the amount of the leakage.

5. CONCLUSION

In many oil fields, pressure monitoring method is used to detect oil leakage in the pipeline system based on pressure measurements. However, this method may cause false leak alarm during pump failure condition unless it is identified to inhibit the false alarm.

In this paper, For simulation, Rockwell Automation Software Products have been used. Compensated mass balance method is implemented for leak detection. This method is capable of dealing with different pipeline operating conditions and recognizes the leakage condition from other abnormal operating conditions. Since the transient model of this method uses flow rate, pressure, temperature and density to calculate the pipeline packing rate, the compensated mass balance model can deal with different operational changes of the pipeline and detects leak easily. Alarms will be activated when there is leakage only.

Different operating conditions, including leakage conditions, have been simulated, presented and discussed.

The simulation reveals that PPA method considers pump failure as a leak, while compensated mass balance method recognizes it.

6. REFERENCES

[1] PEPA. "Yemen Petroleum Exploration and Production Authority)." Internet: http://www.pepa.com.ye, 2012.

[2] Technical Review of Leak Detection Technologies. "Crude Oil Transmission Pipelines. Guidance Document." PLD Technology Conference, Volume I, Alaska Department of Environmental Conservation (ADEC), 2012, pp. 8-14.

[3] J. Zhang. "Designing a Cost Effective and Reliable Pipeline Leak Detection System." Pipeline Reliability Conference, Houston, USA, 1996, pp1-11.

[4] E. McAllister. Pipeline Rules of Thumb. Waltham, USA: Elsevier, 2009, pp 612-615.

[5] G. Geiger. Fundamentals of Leak Detection. Germany: KROHNE Oil & Gas, 2012, pp 10 - 14.

[6] W. Jolly, T. Morrow, J. O'Brien, H. Spence and S. Svednman. New methods for rapid leak detection on offshore pipelines. Department of interior, U.S.A, : Minerals Management Services, 1992, pp 10-14.

[7] American Petroleum Institute. Computational Pipeline Monitoring for Liquid Pipelines. Pipeline Segment API, USA: 2002, pp 9-31.

[8] R. Whaley, R. Nicholas and J. Reet, "Tutorial on Software Based Leak Detection Techniques", Pipeline Simulation Interest Group, pp 4-8, 1992.

[9] G. Geiger. "State of the Art in Leak Detection and Localization." Pipeline Technology Conference, Germany, 2006, pp1-8.

[10] M. Stafford and N. Williams. Pipeline Leak Detection Study. London, UK: 1996, pp 1-13.

[11] E. Odusina, J. Akingbola, D. Mannel, 2008, "Software-Based Pipeline Leak Detection", Department of Chemical Engineering and Materials Science, University of Oklahoma, USA , pp. 10-12.

[12] "Rockwell Automation Software Products." Internet: http://www.engineeringtoolbox.com/.

[13] Hilko den Hollander, Berthold Bollermann "Why is pipeline leak detection more than just installing a flow meter at inlet and outlet?" 2nd Pipeline Technology Conference, Hannover, Germany, 2007, pp 4-8.